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SUMMARY

A laboratory investigation of the focusing of an N-wave at a point and along a line has been conducted. The N-wave was created by a spark at the focus of a parabolic mirror which reflected the N-wave as a plane wave and directed it toward the focusing mirror. Microphone traces of the signature were obtained for various positions of the wave relative to the focus, and schlieren photographs of the passage of the N-wave through the line focus were obtained. The results indicated that the wave underwent a componentwise phase shift of $\pi/2$ radians on passing through a line focus and a corresponding shift of π radians on passing through a point focus, in a manner similar to the focusing of light.

INTRODUCTION

Flight tests (ref. 1) indicate that, under certain supersonic flight conditions, "superbooms" can occur as a result of focusing of the shock-wave structure. Inasmuch as the annoyance and destructive effects of the wave are likely to be enhanced in these superboom regions, it is of interest to study the phenomena. However, the effects of focusing are rather difficult to study in flight tests because of the uncertainty involved in performing an aircraft maneuver that would cause focusing at the precise location of a microphone, and also because of the signature distortion that often occurs as a result of turbulence in the air. A further problem is the expense of flight testing.

Accordingly, an experimental arrangement was designed and built for studying N-wave focusing under controlled laboratory conditions. This system utilizes a spark to generate the N-wave and mirrors to produce the focusing. The focal line produced in this manner is straight whereas a focal line produced by aircraft maneuvers is, in general, curved; however, the phenomena occurring near the focal line should be similar for the two cases. Some experiments were also conducted with three-dimensional focusing (point focus).

The experiments described herein were conducted to evaluate qualitatively two apparently conflicting theories concerning the behavior of a signature in the vicinity of a focus. One of these theories (refs. 2 and 3) indicates that nonlinear effects, occurring

when the acoustic rays tend to converge, prevent a focal point or line from forming. The other theory (refs. 4 and 5) predicts the occurrence of a focus with a shift in the phase of the wave on passing through the focus.

THEORETICAL CONSIDERATIONS

In reference 2, the problem of a concave weak-shock-wave front, propagating along converging rays, is analyzed. The results of the analysis indicate that focusing does not actually occur, but that the rays and wave front bend in such a manner as to avoid focusing, the rays bending away from each other and the wave front becoming convex (fig. 1(a)). In reference 3, a similar discussion is given with emphasis on the sonic-boom problem. Here again the conclusion indicates that caustics, or focal lines, do not occur. On the other hand, the geometrical acoustics solution, corresponding to the theory of geometrical optics, predicts that focusing does actually occur (fig. 1(b)), with a shift in the phase of the wave in passing through the focus. (See, for example, refs. 4 and 5.) This theory predicts that, for the two-dimensional focusing of a sinusoidal acoustic wave, a cusp or caustic line is formed, with a phase shift of $\pi/4$ radians on the caustic and a shift of $\pi/2$ radians on complete passage through the caustic.

For a finite amplitude wave, such as an N-wave, the pressure in the wave may depart considerably from the sinusoidal form. Then the phase-shifting phenomenon becomes somewhat more complicated. The original pressure-distribution function must be resolved into its Fourier components, and each component shifted in phase. Then the correct shifted pressure distribution is synthesized from the resulting terms. The results of such a calculation for an N-wave (fig. 2(a)) give pressure distributions like those of figures 2(b), 2(c), and 2(d) for component shifts of $\pi/4$, $\pi/2$, and π radians, respectively. A shift of $\pi/2$ radians occurs whenever the wave passes through one of its centers of curvature. If the two centers of curvature are coincident, as for a converging spherical wave, the component phase shift is $\pi/2$ radians at the focus and π radians on passage through the focus; these component phase shifts result in pressure signatures of the forms shown in figures 2(c) and 2(d), respectively.

The geometrical optics solution is precise only in the limit of vanishing wavelength; nevertheless, it represents a valid approximation if the wavelength is short in comparison with other relevant length dimensions, such as the width of a reflecting or diffracting surface and the focal length of a reflecting surface. When flight conditions are such that the possibility of sonic-boom focusing exists, the wavelengths involved are normally small in comparison with the distance the wave travels to the point at which focusing should occur. Thus, it would appear that the conditions for validity of the geometrical optics solution

are satisfied. On the other hand, the fact that the wave is not a simple acoustic wave but contains weak shocks would indicate, according to references 2 and 3, that focusing does not actually occur.

Thus, in designing laboratory experiments to determine which of the two theories gave results more nearly in accord with the actual physical phenomena involved in sonic-boom focusing, an effort was made to satisfy the following conditions:

(1) N-wave overpressures of the same order as those occurring under flight conditions

(2) Wavelength much smaller than mirror width

(3) Wavelength much smaller than mirror focal length

APPARATUS AND PROCEDURE

Mirrors

The mirror, spark, and microphone arrangement shown in figure 3 was used to produce two- or three-dimensionally-focused N-waves. The type of focusing was determined by the selection of mirror M_2. In either case, mirror M_1 was an axisymmetric parabolic mirror with a 20.32-cm focal length. For three-dimensional focusing, mirror M_2 was also an axisymmetric parabolic mirror with a 15.24-cm focal length. For two-dimensional focusing, it was necessary to fabricate a two-dimensional mirror. This mirror was fabricated by rolling a 1.27-cm-thick rectangular sheet of highly polished aluminum into the shape of a segment of a cylinder, the cross section of which was a parabola. This mirror also had a focal length of 15.24 cm and was 30.48 cm in width and 45.72 cm in height.

Spark Electrodes and Power Supply

The spark at the focal point of mirror M_1 was produced by a 0.254-mm spark gap between the pointed tips of two tungsten electrodes. The electrodes were 3.175 mm in diameter and 20.32 cm in length. They were mounted at an angle of 60° with respect to each other in a plane perpendicular to the mirror axis. This arrangement was found to produce negligible diffraction effects in the reflected acoustical wave front. The spark power was furnished by switching a small capacitor charged to a high dc voltage (nominally 6 kV) across the electrodes by means of a 5C22 thyratron tube. A high-voltage dc power supply which had a rated output of 10 kV at 1 ampere was used to charge the capacitor.

Microphone System

A commercially available, condenser-type microphone system was used to measure the pressure response of the N-wave. The microphone consisted of a 6.35-mm-diameter condenser-type cartridge which was connected to a cathode follower by a flexible adapter. Also included in the system was a matching power supply which furnished the polarization voltage to the microphone. The normal incidence free-field frequency response of the microphone was flat within ±2 dB from 0.03 to 100 kHz. The microphone sensitivity was calibrated by a pistonphone and was found to be within 2 percent of the manufacturer's stated value of 2265 $\frac{\mu V}{N/m^2}$ at the cathode-follower output. The pressure input from the pistonphone was only about 1 percent of the peak values measured. No attempt was made to calibrate the microphone at higher pressure inputs for which a linear response was assumed. Consequently, the accuracy of the measured amplitudes would be influenced by any nonlinearity of the microphone sensitivity. However, it is the signature shapes and not the absolute magnitudes of the pressures that are significant in this study.

The output waveform from the microphone was displayed and photographed on an oscilloscope. The oscilloscope incorporated a continuously variable time-delaying sweep feature which insured that only the wave which was reflected from the spark to mirror M_1 to mirror M_2 and then to the microphone was recorded. This delay prevented erroneous recording of direct or reflected wave shapes.

The microphone rise time is of the order of 4 μsec. The rise-time capability of the microphone becomes increasingly important as the period of the N-wave becomes shorter since the shock-wave rise time is negligible. Both the N-wave amplitude and period are influenced somewhat by the spark-gap dimensions and primarily by the energy of the spark (size of capacitor at a constant voltage). Therefore, it was of interest to examine the suitability of this size and type microphone for accuracy with both short- and long-duration N-waves produced by the spark. For a low-energy spark (0.01 joule), the period was 12 μsec and the rise time was 4 μsec; consequently, the recording time for displaying the nose and tail shocks was 4 μsec (1/3 period) so that the wave shape more nearly resembled one cycle of a sine wave rather than an N-wave (fig. 4(a)). Increasing the energy of the spark (1.9 joules) increased the wavelength and the amplitude, as can be seen in figure 4(b). The rise time occupied a less appreciable portion of the period (1/10 period), and in this respect the signature more nearly resembled an N-wave. However, even for these longer signatures, considerable distortion could occur as a result of the limited microphone response. This problem was discussed in some detail in reference 6, but it was even more severe in the present investigation because the signatures studied had periods even shorter than those studied in reference 6. In the present investigation, the ratio of wavelength to the dimensions of the microphone was so

small that interference effects, particularly diffraction, were responsible for some of the distortion in the pressure signatures. In fact, interference caused by the position and dimensions of the slots in the diaphragm protective grid cover was so great that the grid was removed for recording the signatures. However, in view of the fact that the incident pressure signatures (fig. 5) closely resembled an ideal N-wave, the limitations of the microphone were such that the response was sufficient to examine the progress of the N-wave through a focal point or line in order to observe any focusing or phase shifting that might occur.

Procedure for Locating Acoustical Focus

A point light source was located at the focal point of mirror M_1, and both mirror M_1 and mirror M_2 were adjusted so that the light rays were parallel and uniform in intensity. The microphone was positioned on an optical rail with the sensitive diaphragm surface at the optical focal point of mirror M_2 in such a manner that its longitudinal axis was at an angle of 38° to the center line of the mirrors and the diaphragm was far enough from the edge of mirror M_2 in order to avoid edge effects. The point source was then replaced by the spark gap. The spark gap was triggered, and the microphone output was observed on the oscilloscope. The microphone was then moved along the optical rail both inside (toward mirror M_2) and outside (away from mirror M_2) the optical focal point until an acoustical focal point was found. These focal points (optical and acoustical) differed by a slight amount because the silvered optical surface was on the back side of the mirrors; consequently, the difference in transit distance between the optical focusing and the acoustical focusing was twice the thickness of the glass mirrors. The acoustical focal point was selected as the location where the largest peak overpressure was produced by the microphone. The delaying sweep was then adjusted so that only the desired portion of the microphone output was observed and photographed. The microphone was then positioned near the surface of mirror M_2 (inside the focal point) and then moved in successive increments through the focal point and outside the focal point; thereby, the microphone traversed a single acoustical ray. It was necessary to adjust the time delay continuously in order to compensate for the consequent difference in the acoustical-ray path length.

RESULTS AND DISCUSSION

Figure 5(a) shows oscillograms of the pressure signature taken along a ray through the focal point of the two-dimensional mirror at stations inside the focus, at the focus, and outside the focus. The corresponding signatures for three-dimensional focusing are shown in figure 5(b).

These experimental waveforms are to be compared with the computed signatures of figure 2. Although the signatures are modified somewhat by the microphone response and, possibly, by effects of diffraction, the results clearly indicate the occurrence of the phase shift predicted by the geometrical optics theory. At the focus of the two-dimensional mirror, this phase shift by component is $\pi/4$ radians. The total shift is $\pi/2$ radians on complete passage through the focus. At the focus of the three-dimensional mirror, the phase shift is $\pi/2$ radians. On passage through the focus, the shift is π radians, a complete inversion of the wave. Such a nearly discontinuous initial expansion would probably be difficult to achieve in a direct wave.

These records represent typical data. Although each set of records was taken by using one specific capacitor to energize the spark, similar results were obtained with other capacitors throughout a range from 0.1 to 0.5 μF. These capacitor values gave N-wave overpressures, before focusing, from 1.48 psf (70.86 N/m^2) to 4.61 psf (220.8 N/m^2).

Some typical plots showing the variation of amplitude with distance along a ray through the focus are provided in figure 6. Although these data indicate the occurrence of significant amplification in the vicinity of a focus, the very large amplitudes predicted by strict ray-tube theory are not obtained. These amplitudes are influenced by such factors as the wavelength, microphone response, mirror astigmatism, and mirror dimensions. Consequently, it is doubtful whether any conclusion concerning the variation of amplitude in the neighborhood of the focus of a wave resulting from a supersonic flight could be drawn from figure 6.

Figure 7 shows a sequence of schlieren photographs of an N-wave as it approaches the two-dimensional mirror as a plane wave, is reflected as a converging cylindrical wave, and passes through the focal line. In interpreting these photographs, one should bear in mind that as the wave moves from right to left the compressions are indicated by the dark areas and the expansions are indicated by the light areas, but this feature is reversed as the wave moves from left to right.

CONCLUDING REMARKS

Results of a laboratory investigation indicated that shock-wave behavior in the vicinity of a point or a line focus followed the laws of geometrical acoustics. When a spark-produced N-wave, having an amplitude of the order of that produced on the ground by a supersonic flight, was reflected from a two-dimensional parabolic mirror, a line focus was produced. When the wave passed through the focus, it underwent a componentwise

shift in phase of $\pi/2$ radians. The corresponding experiment performed with a three-dimensional mirror gave a phase shift of π radians resulting in a complete inversion of the wave.

Langley Research Center,
    National Aeronautics and Space Administration,
        Langley Station, Hampton, Va., April 30, 1969,
            126-61-06-09-23.

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Shock front

----- Ray

------> Direction of propagation
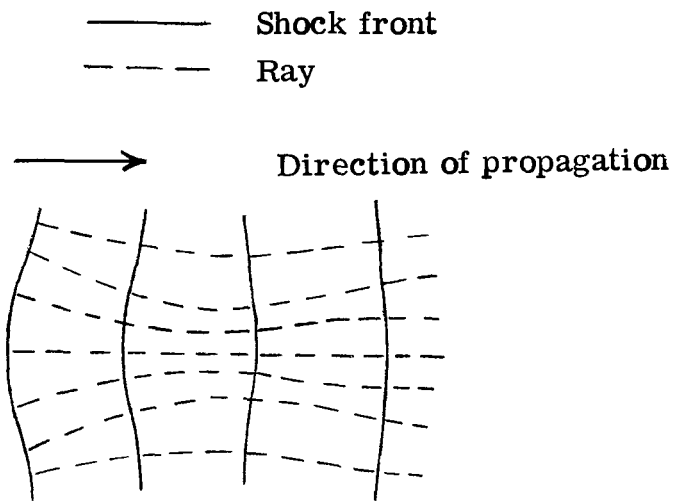
(a) Whitham theory.
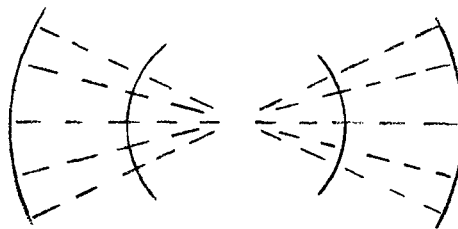
(b) Geometrical acoustics theory.

Figure 1.- Diagram showing rays and shock positions as predicted by the conflicting theories.

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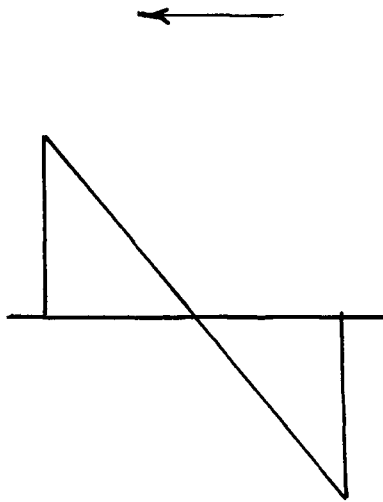
(a) Undistorted N-wave
pressure signature.
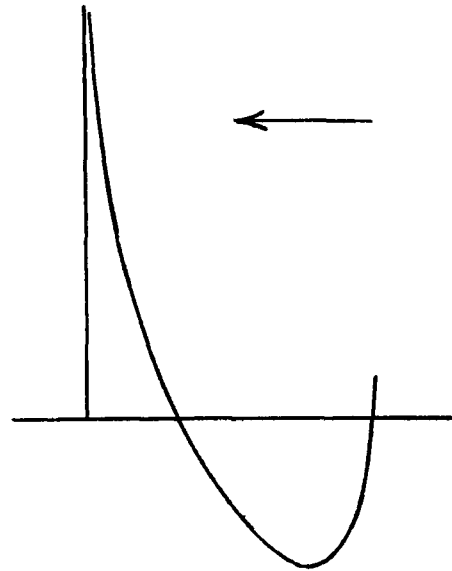
(b) Signature with component phase
shift of $\pi/4$ radians.
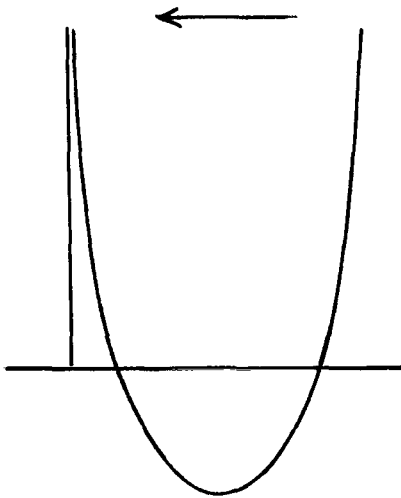
(c) Signature with component phase
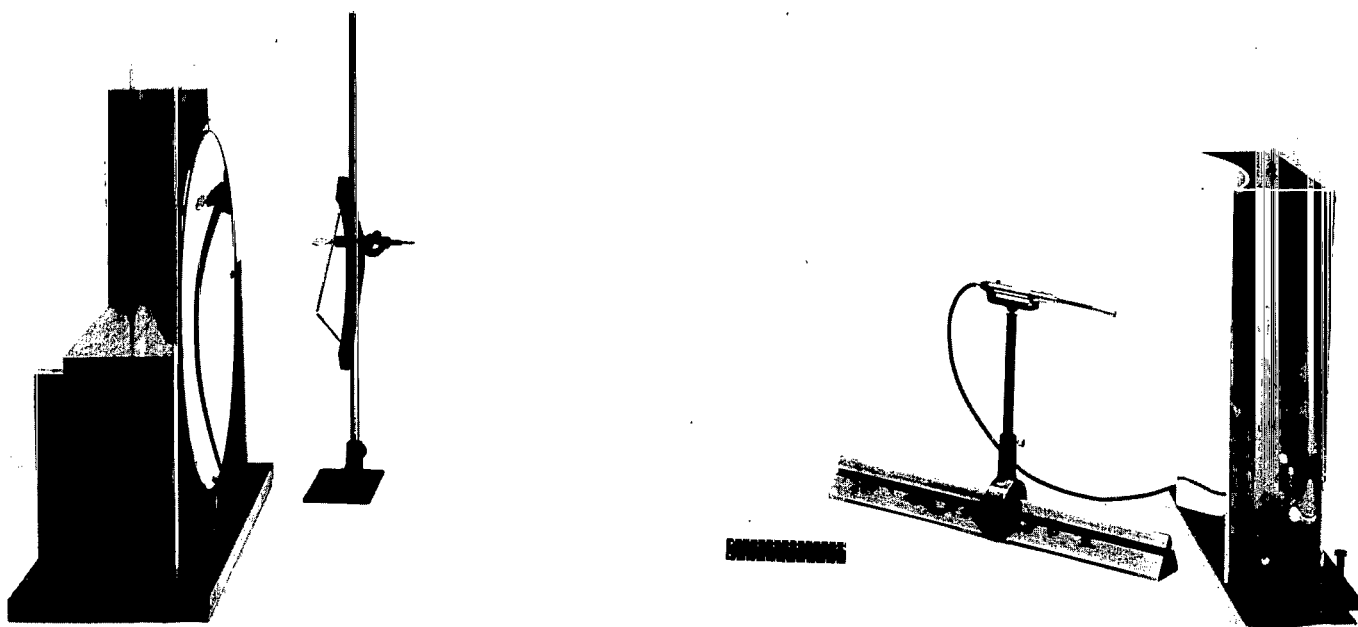shift of $\pi/2$ radians.
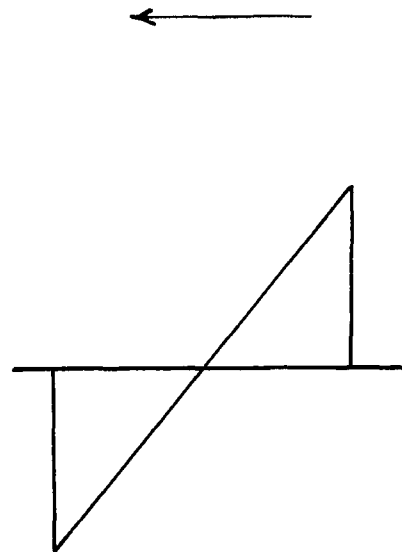
(d) Signature with component phase
shift of π radians.

Figure 2.- Calculated shapes of the pressure signature as the wave passes. Arrow indicates direction of wave propagation.
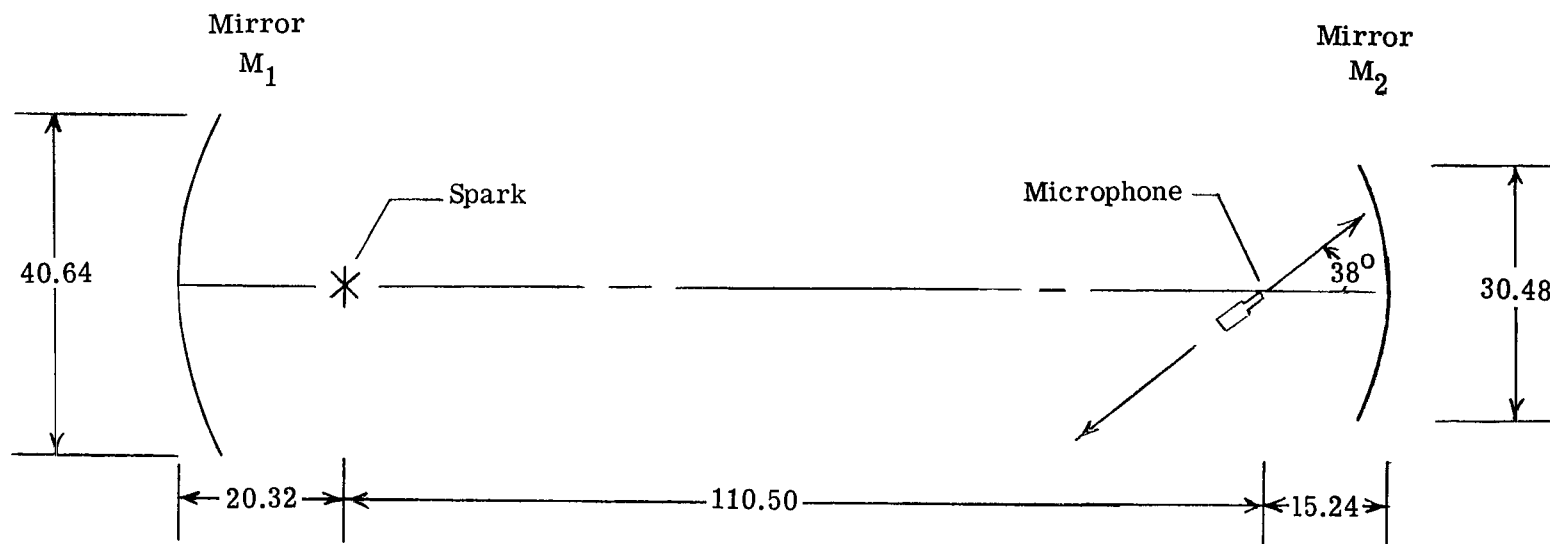
(a) Schematic diagram. Top view. All dimensions in centimeters.

Figure 3.- Test apparatus.

(b) Photograph of two-dimensional focusing arrangement.

Figure 3.- Continued.
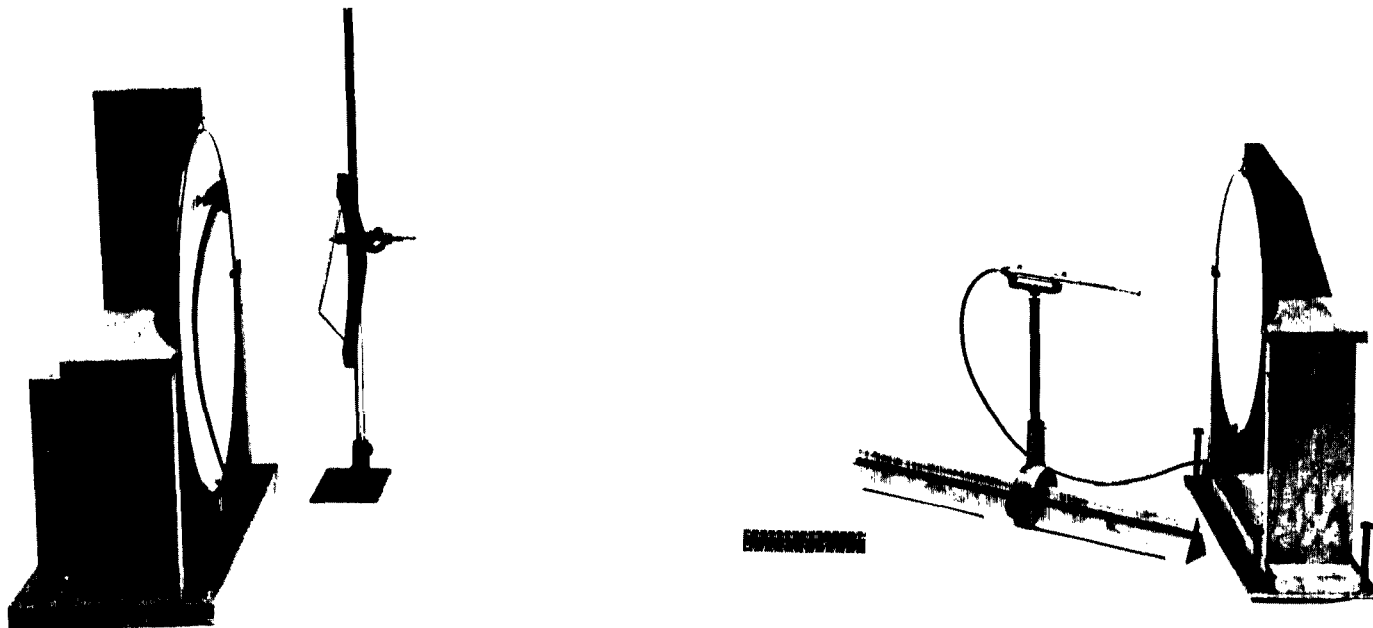
(c) Photograph of three-dimensional focusing arrangement.

Figure 3.- Concluded.

L-69-1407
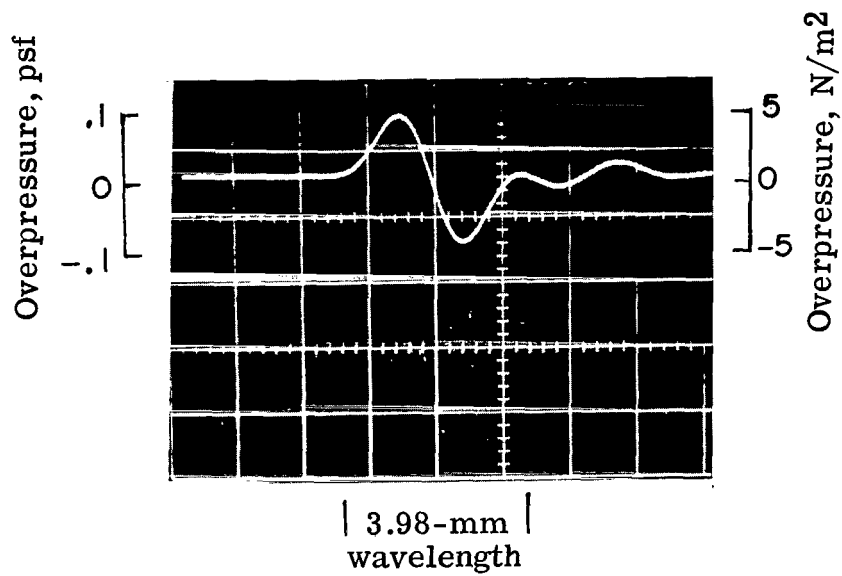
(a) Spark energy, 0.01 joule; oscilloscope sweep speed, 5 μsec/cm.
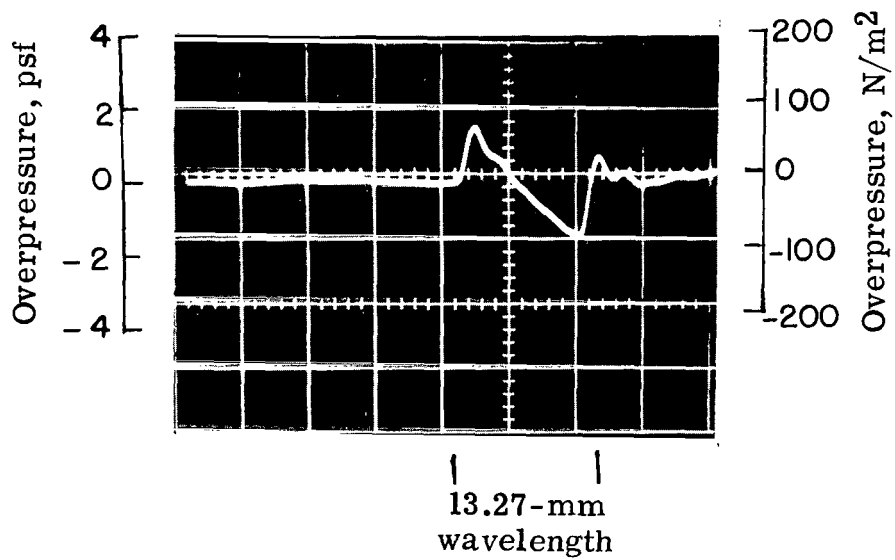
(b) Spark energy, 1.9 joules; oscilloscope sweep speed, 20 μsec/cm.

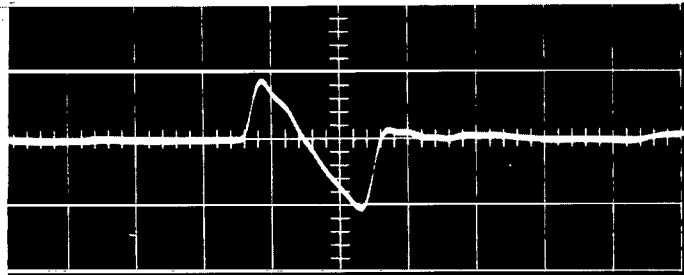Figure 4.- Effect of spark energy on waveform.
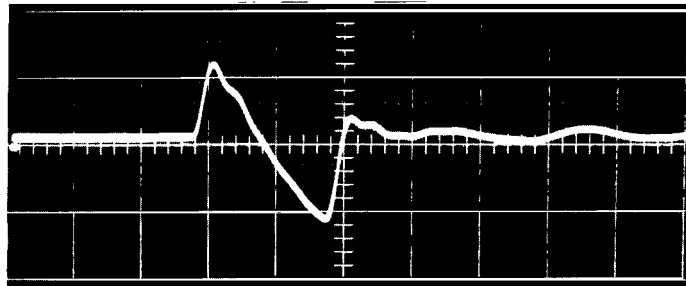
Incident N-waveforms
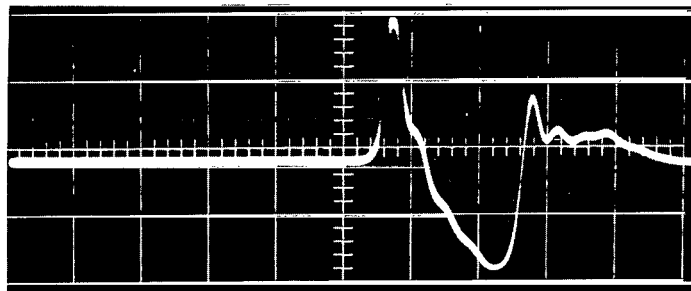
Waveform at focus, with component
phase shift of $\pi/4$ radians
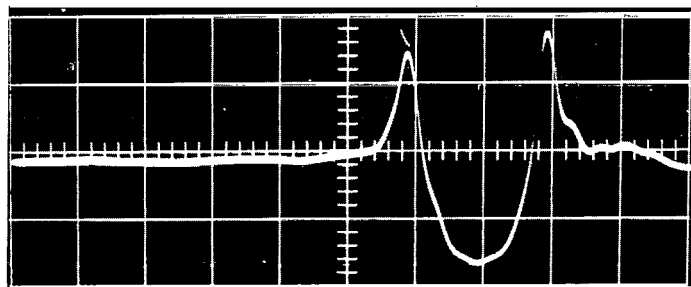
Waveform after passage through focus,
with component phase shift of $\pi/2$ radians
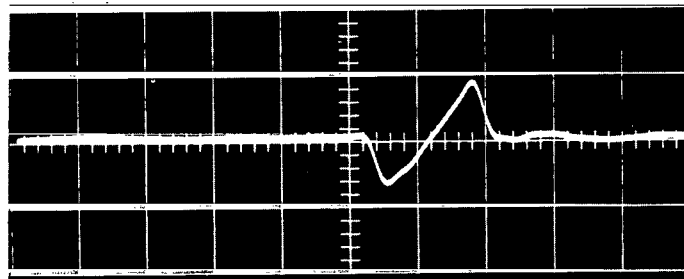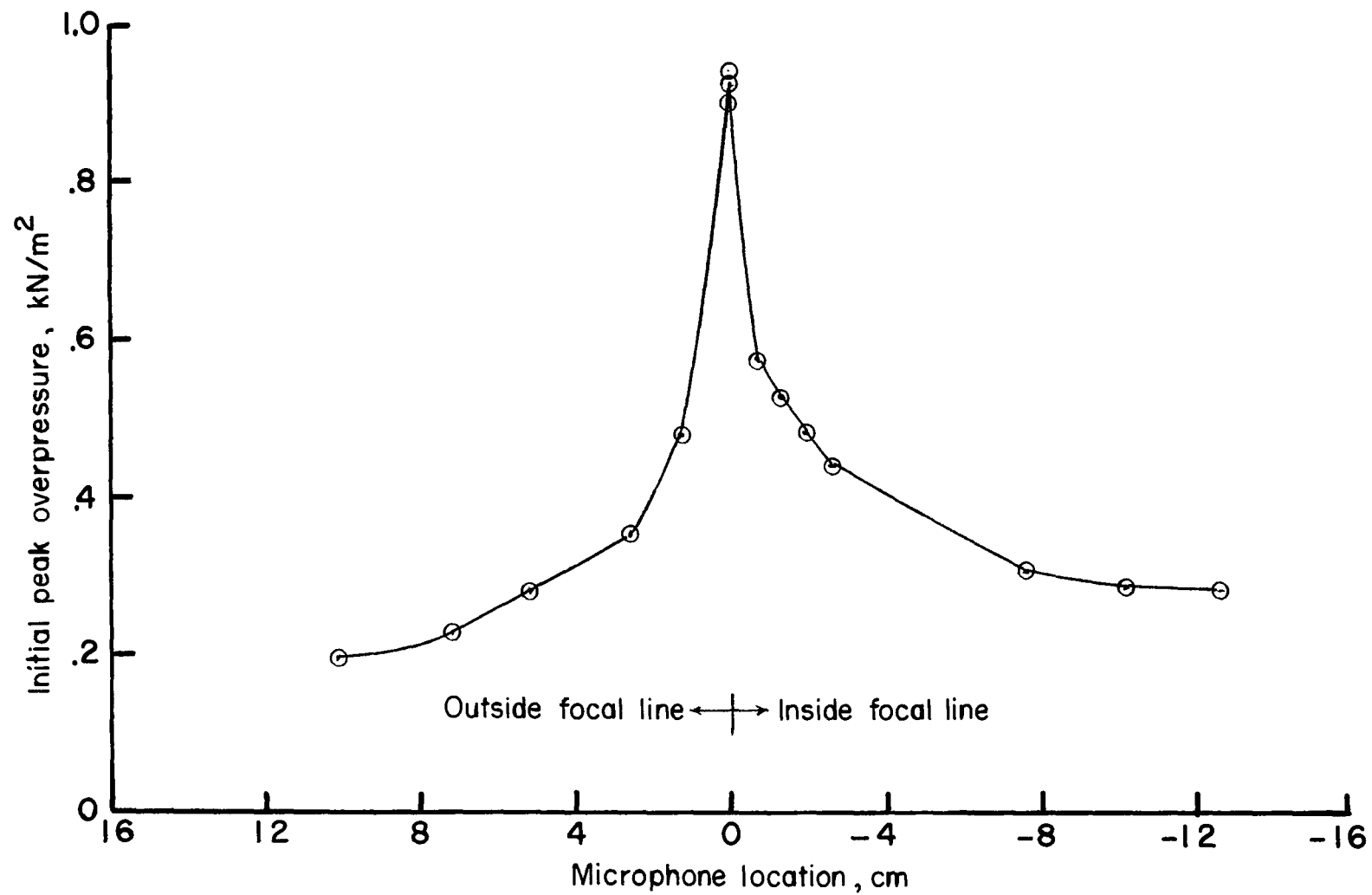
(a) Two-dimensional focusing.

Figure 5.- N-wave focusing effects. Oscilloscope sweep speed, 20 μsec/cm; spark energy, 9.0 joules.

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Incident N-waveforms
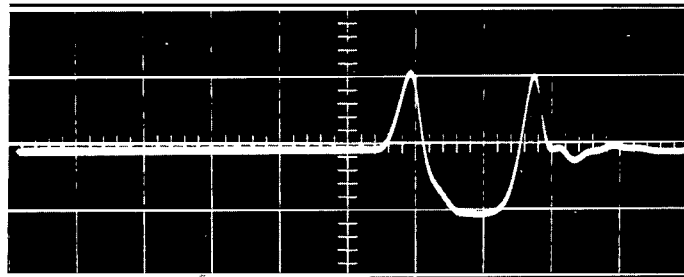
Waveform at focus, with component
phase shift of $\pi/2$ radians

Waveform after passage through focus,
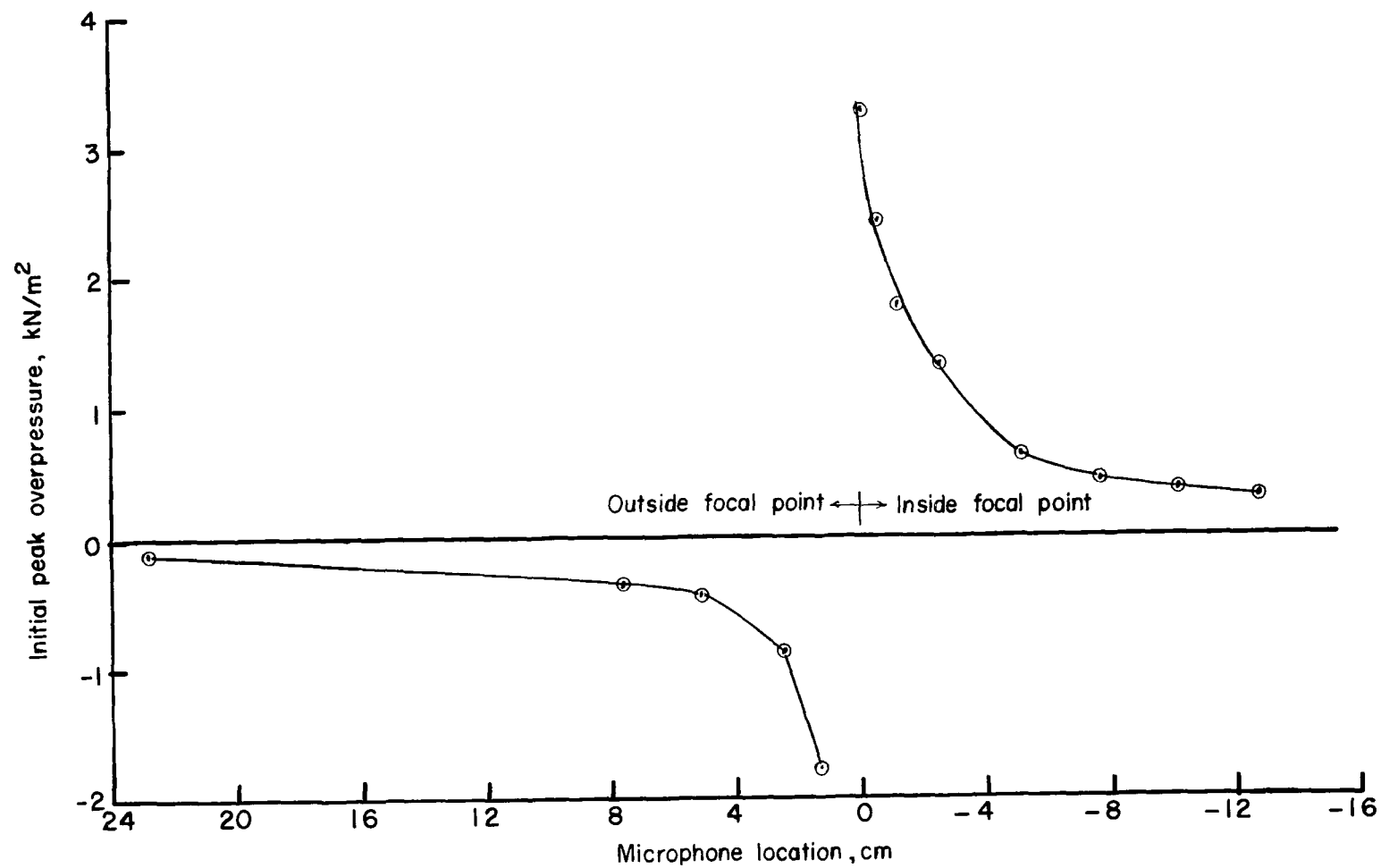with component phase shift of π
radians

(b) Three-dimensional focusing.

Figure 5.- Concluded.

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(a) Passage through line focus.

Figure 6.- Variation of initial peak overpressure with distance from focus.

(b) Passage through point focus.
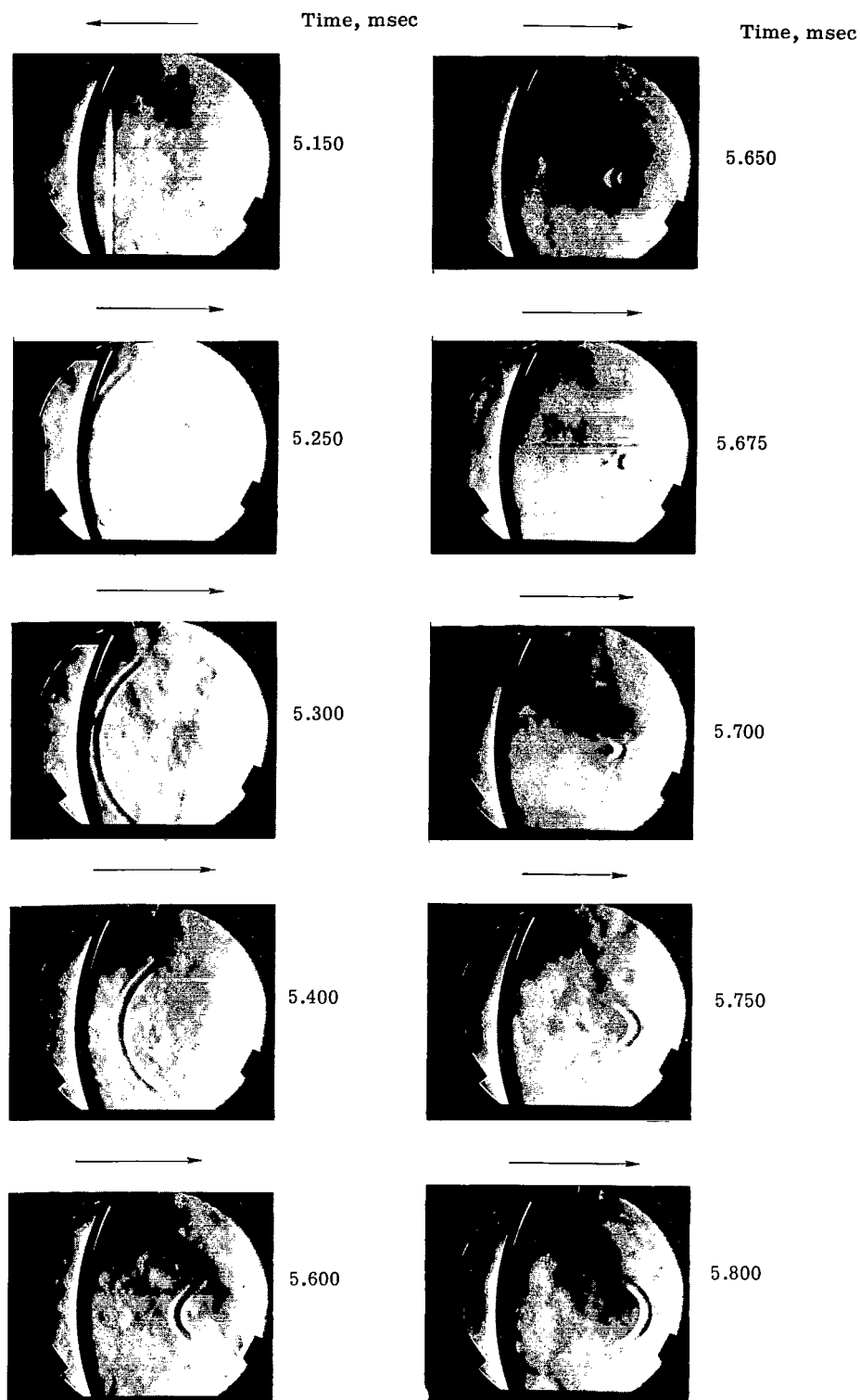
Figure 6.- Concluded.

Figure 7.- A schlieren time sequence of a converging cylindrical shock wave passing through the focal line of a two-dimensional mirror.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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